(STANDARD) SOLAR MODELS, NEUTRINOS AND COMPOSITION

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MAGELLAN WORKSHOP - CONNECTING NEUTRINO PHYSICS AND ASTRONOMY
@ DESY, HAMBURG, MARCH 2016

Calibration of SSM

SSM assumes

Initially fully mixed composition due to convection in pre-MS
constant solar mass $M_\odot$ and known age 4.57 Gyr

3 free parameters to match 3 observables –
- Convection parameter
- Initial composition – metal and helium content

$$m_{ij} = \frac{\partial \log c_i}{\partial \log p_j}$$

	α_{mlt}	Y_{ini}	Z_{ini}
$\mathrm{L}_\odot$	0.06	2.35	-0.73
$\mathrm{R}_\odot$	-0.19	0.56	-0.14
$(\mathrm{Z/X})_\odot$	0.06	0.08	1.11

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$(Z/X)_\odot$ has changed noticeably in last 10-15 years -- > $Z_{\rm ini}$ & $Y_{\rm ini}$ affected

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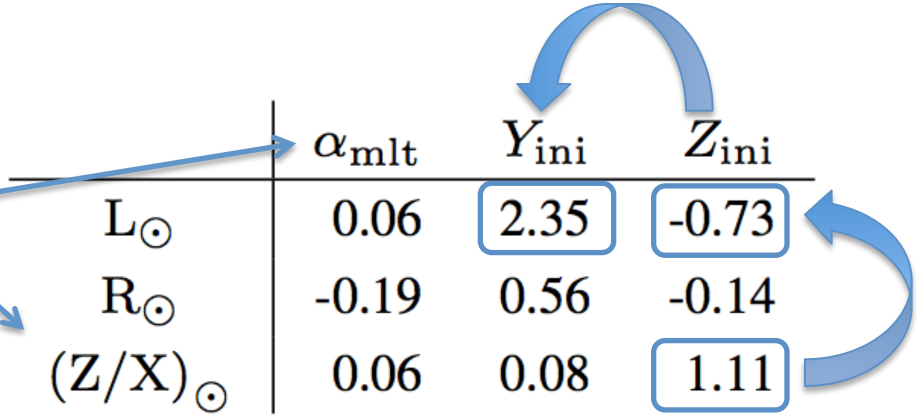

	$\alpha_{\rm mlt}$	$Y_{\rm ini}$	$Z_{\rm ini}$
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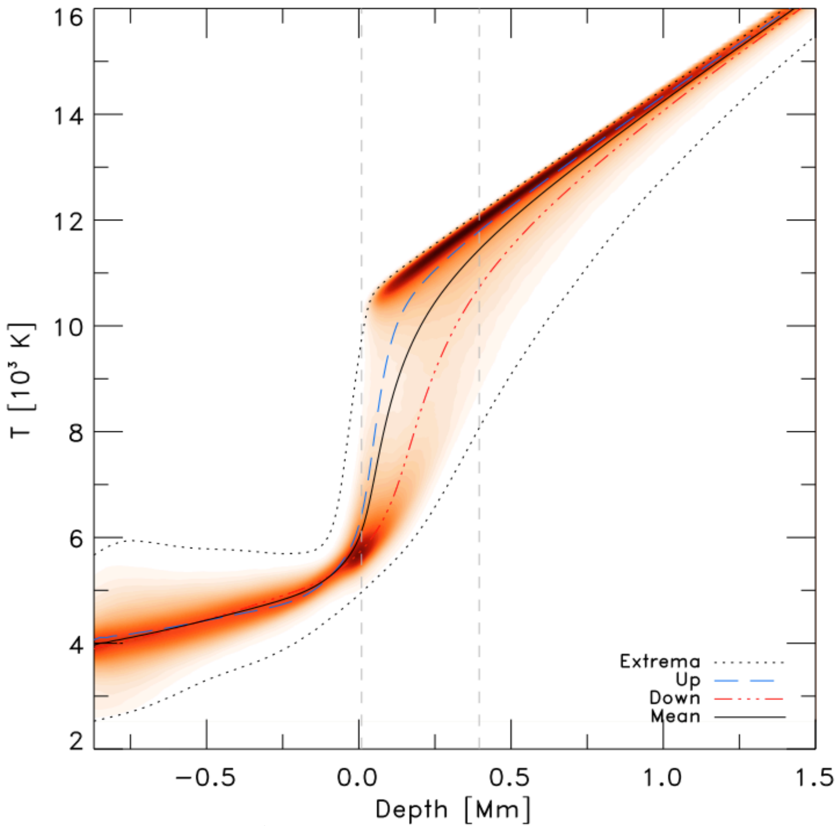
Solar abundances based on 3D atmospheres

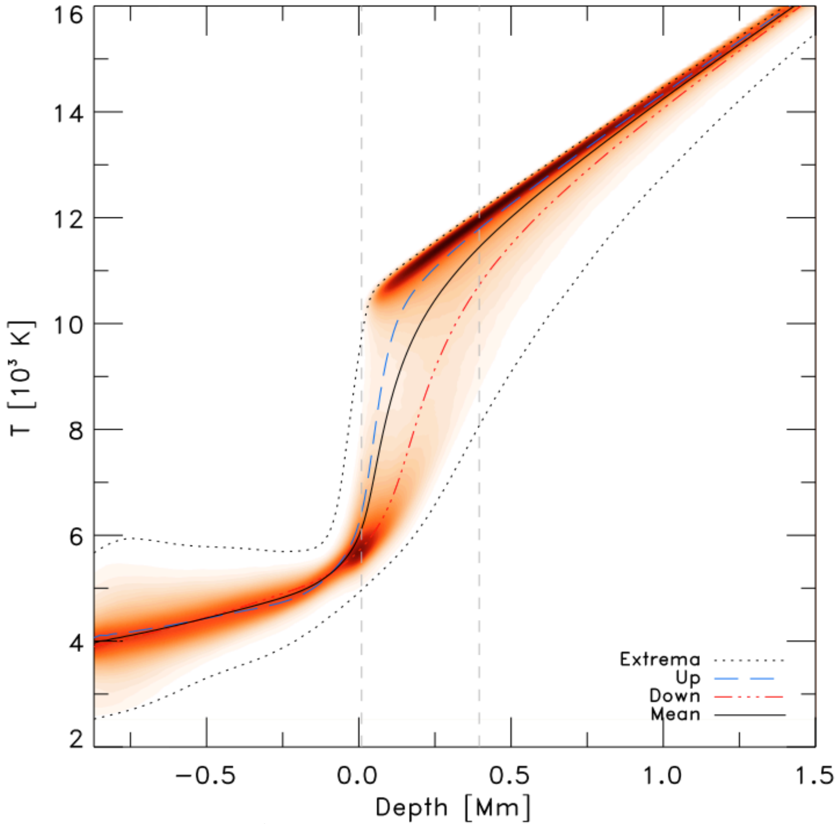


Magic et al. 2014

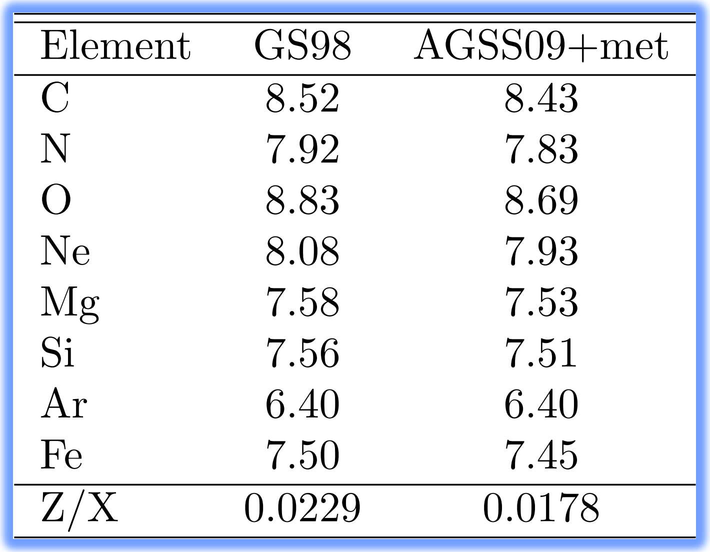
Fluctuations around mean + nonlinearity of Planck function (T) and line formation (T & ρ)

-- > spectral analysis in 3D cannot be represented by 1D (Uitenbroek & Criscuoli 2011)

Solar abundances based on 3D atmospheres (+NLTE + atomic data)



Magic et al. 2014



Element	GS98	AGSS09+met
C	8.52	8.43
N	7.92	7.83
O	8.83	8.69
Ne	8.08	7.93
Mg	7.58	7.53
Si	7.56	7.51
Ar	6.40	6.40
Fe	7.50	7.45
Z/X	0.0229	0.0178

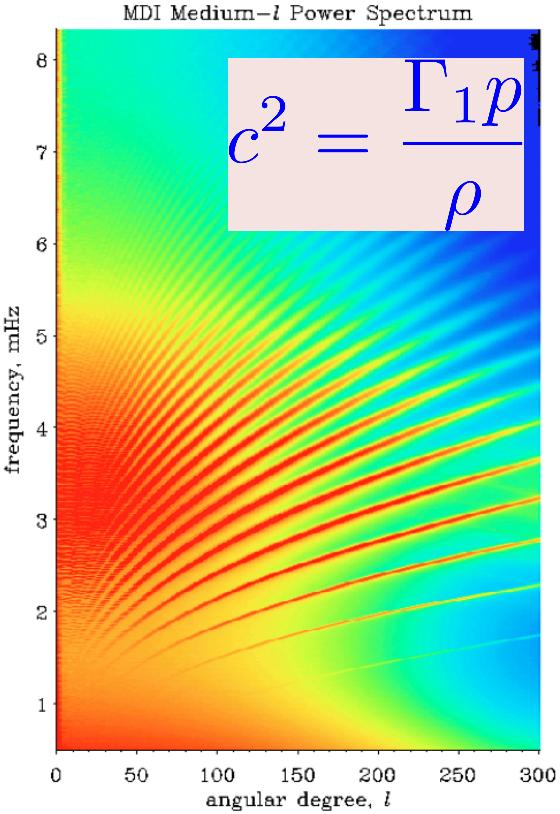
$\log(n_x/n_H)+12$

“Sub-solar” solar metallicity

CNO(Ne)~30-40%

refractories~10%

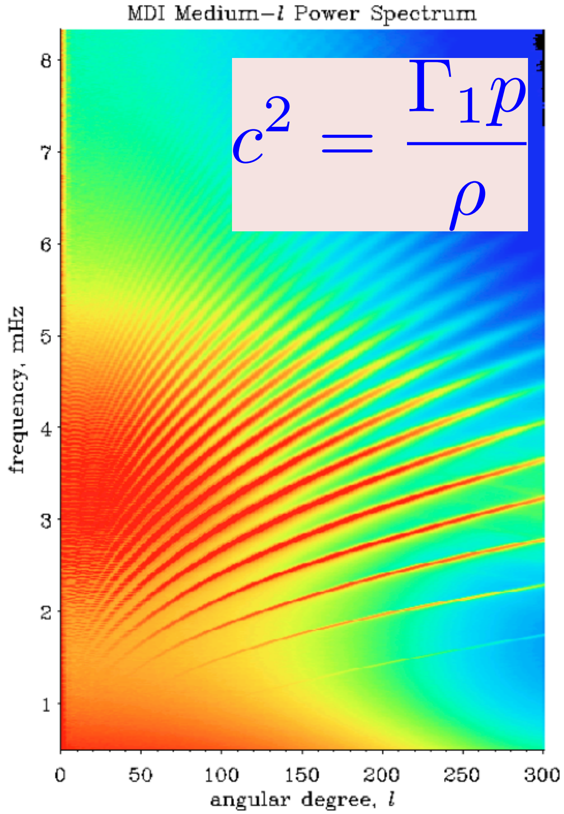
Helioseismology



$$c^2 = \frac{\Gamma_1 p}{\rho}$$

acoustic standing waves (p-modes)
typical period 5 minutes (~ 3 mHz)
amplitudes ~ few cm/s in radial velocity
~ parts per million in brightness

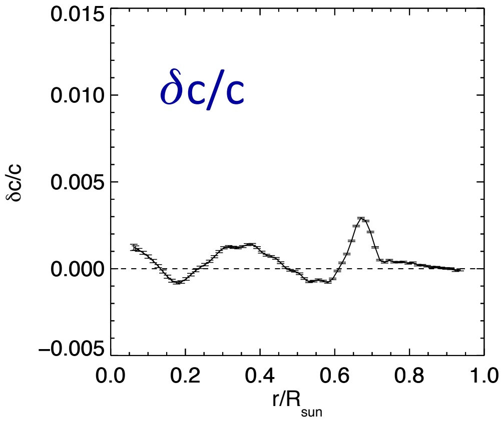
Helioseismology

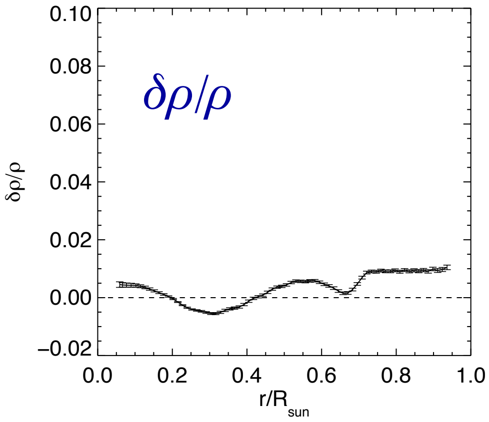


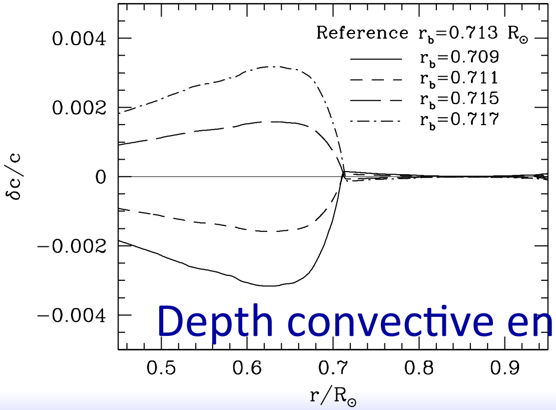
$$c^2 = \frac{\Gamma_1 p}{\rho}$$

Inversion of profiles of solar properties: c^2, r, Γ_1, Y

$$\frac{\delta\omega_i}{\omega_i} = \int K^i_{c^2,\rho}(r)\boxed{\frac{\delta c^2}{c^2}(r)}dr + \int K^i_{\rho,c^2}(r)\boxed{\frac{\delta\rho}{\rho}(r)}dr + F_{surf}(\omega_i)$$





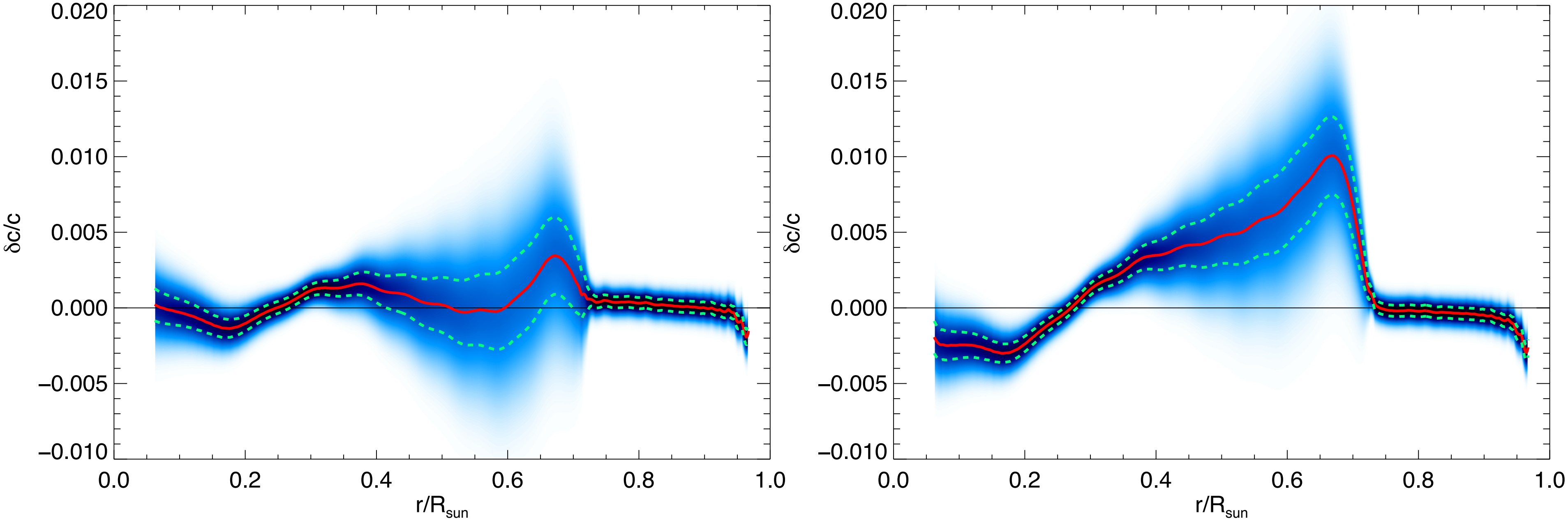


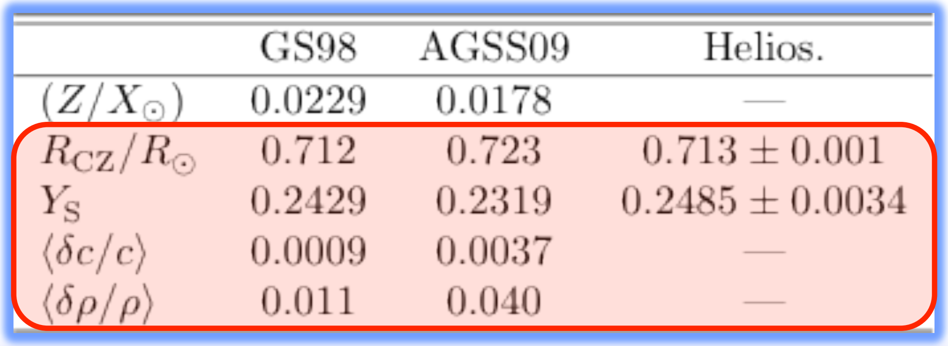
Depth convective envelope

acoustic standing waves (p-modes)
typical period 5 minutes (~ 3 mHz)
amplitudes ~ few cm/s in radial velocity
~ parts per million in brightness

Changes in helioseismic properties

Sound speed profiles based on Monte Carlo simulations, 10^4 SSMs (Vinyoles et al. 2016 in prep)





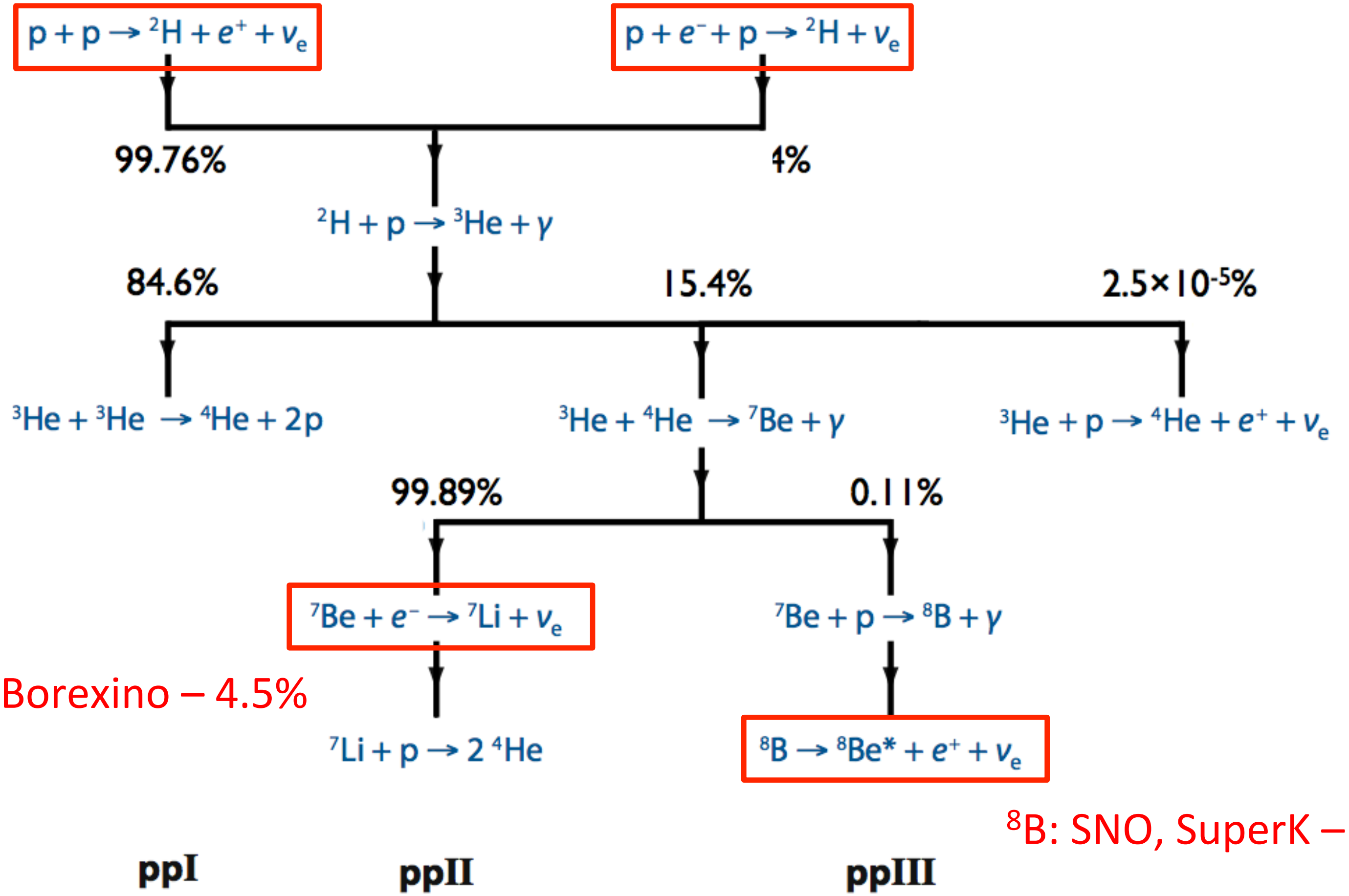
	GS98	AGSS09	Helios.
$(Z/X_\odot)$	0.0229	0.0178	—
$R_{CZ}/R_\odot$	0.712	0.723	0.713 ± 0.001
Y_S	0.2429	0.2319	0.2485 ± 0.0034
$\langle \delta c/c \rangle$	0.0009	0.0037	—
$\langle \delta \rho/\rho \rangle$	0.011	0.040	—

High-Z models are preferred

Solar neutrinos

Borexino: pp(10% - 2014)

pep(20% - 2012)



$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$

$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$

99.76%

4%

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

84.6%

15.4%

$2.5 \times 10^{-5}\%$

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

99.89%

0.11%

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$

${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{7}Be$: Borexino – 4.5%

${}^{7}Li + p \rightarrow 2\,{}^{4}He$

${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$

${}^{8}B$: SNO, SuperK – 3%

ppI

ppII

ppIII

Solar neutrinos

Model fluxes based on Solar Fusion II (Adelberger et al. 2011)
Solar fluxes determined from all ν data (Serenelli et al. 2011)

Flux	SFII-GS98	SFII-AGSS09	Solar
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$
pep	$1.44(1 \pm 0.011)$	$1.47(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$
hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	$18(1^{+0.4}_{-0.5})$
^{7}Be	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$
^{8}B	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$5.00(1 \pm 0.03)$
^{13}N	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7
^{15}O	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.2
^{17}F	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	≤ 59
$\chi^2/P^{\rm agr}$	3.5 / 90%	3.4 / 90%	

Luminosity constraint: $L_\odot = L_{\rm nuc}$

Experimental uncertainty

No discrimination between models

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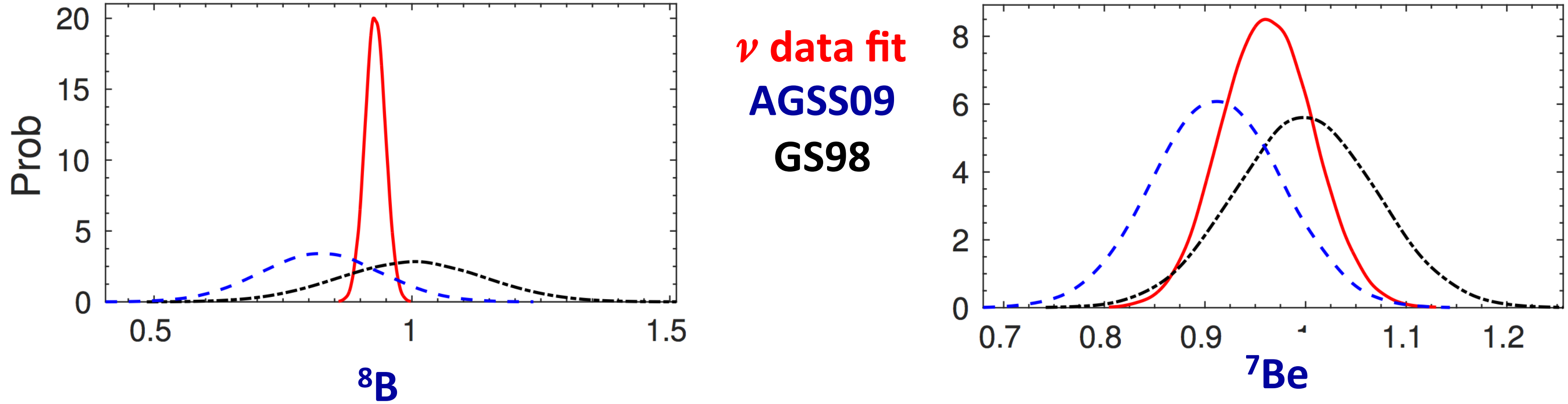
Updated ν-data from Borexino – combined SNO phases – SuperK Phase IV: Bergstrom et al. 2016

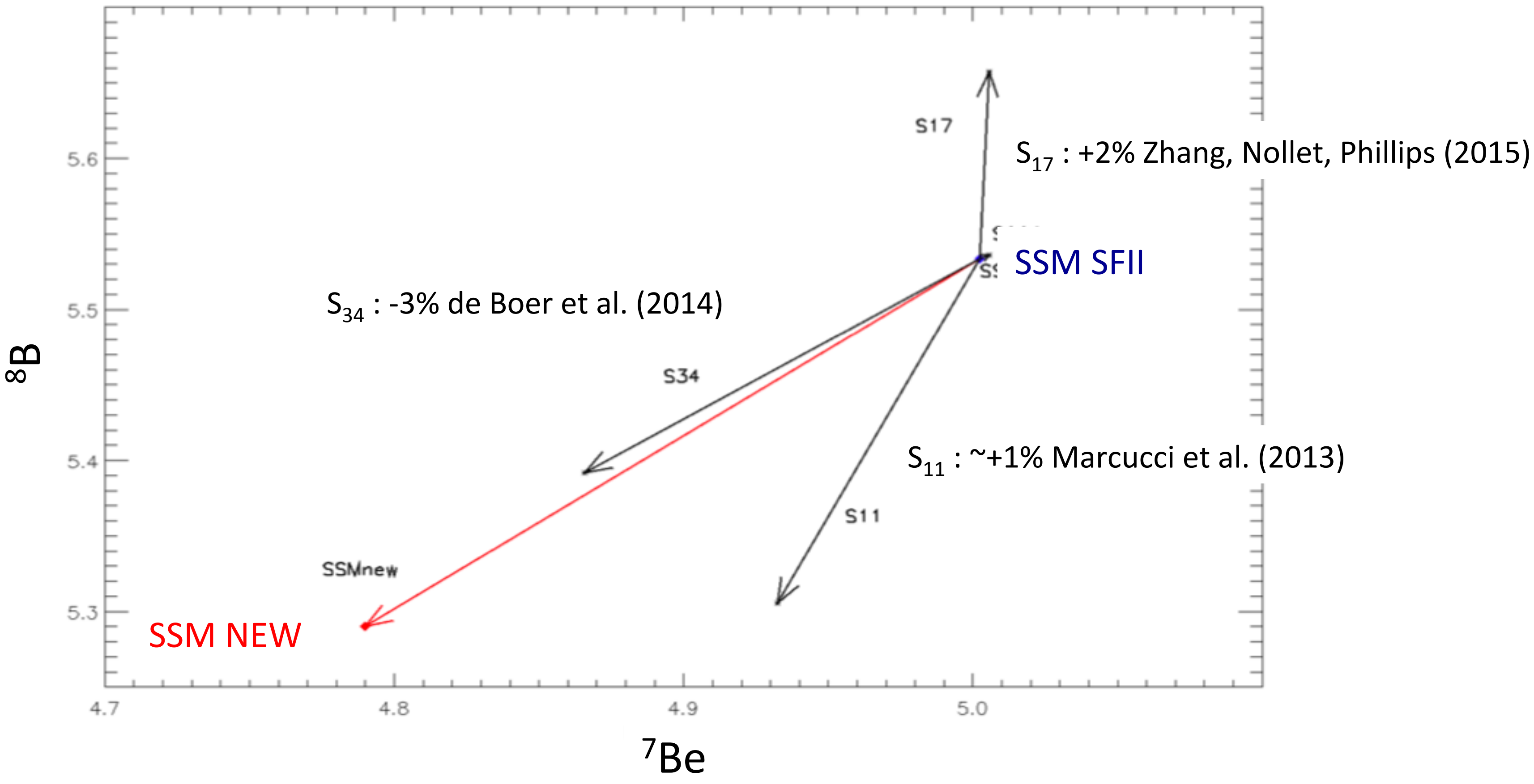


What do we know so far (with 2011 solar models)…

All robust helioseismic probes favor high-Z solar models

Solar neutrino fluxes, mostly ^{8}B and ^{7}Be, are matched equally (very) well by high-Z and low-Z models

Updates in nuclear rates since Solar Fusion II



S_{17} : +2% Zhang, Nollet, Phillips (2015)

SSM SFII

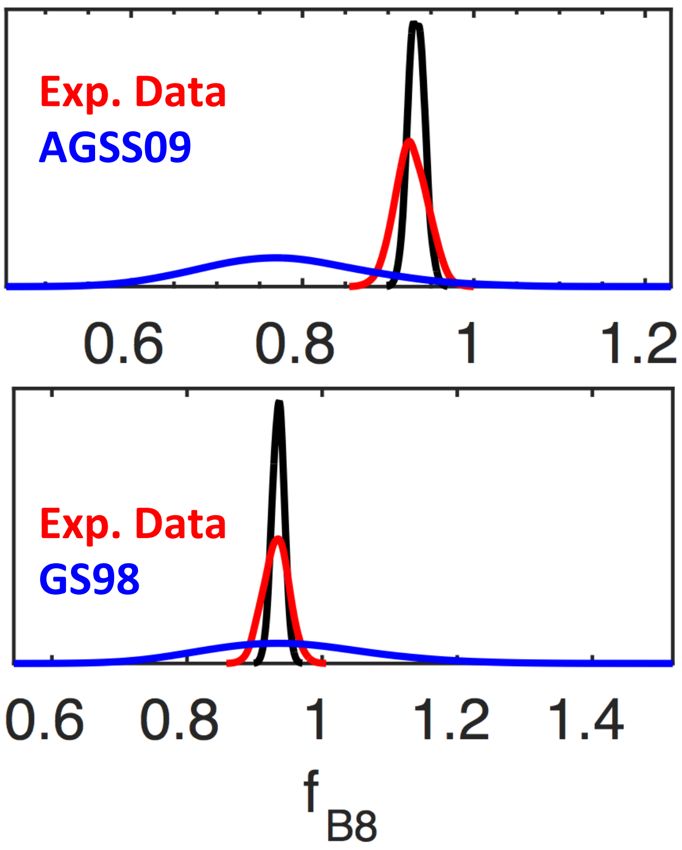
S_{34} : -3% de Boer et al. (2014)

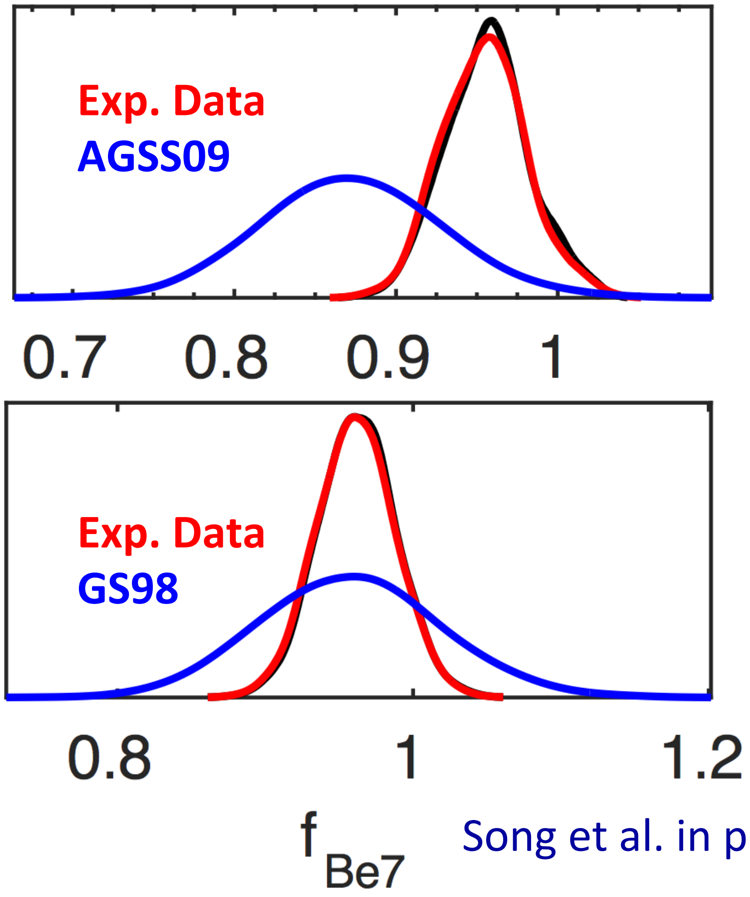
S_{11} : ~+1% Marcucci et al. (2013)

SSM NEW

^{8}B decreases 5% (experimental error 3%)
^{7}Be decreases 4% (experimental error 4.5%)

Solar neutrinos now favor high-Z (GS98) model



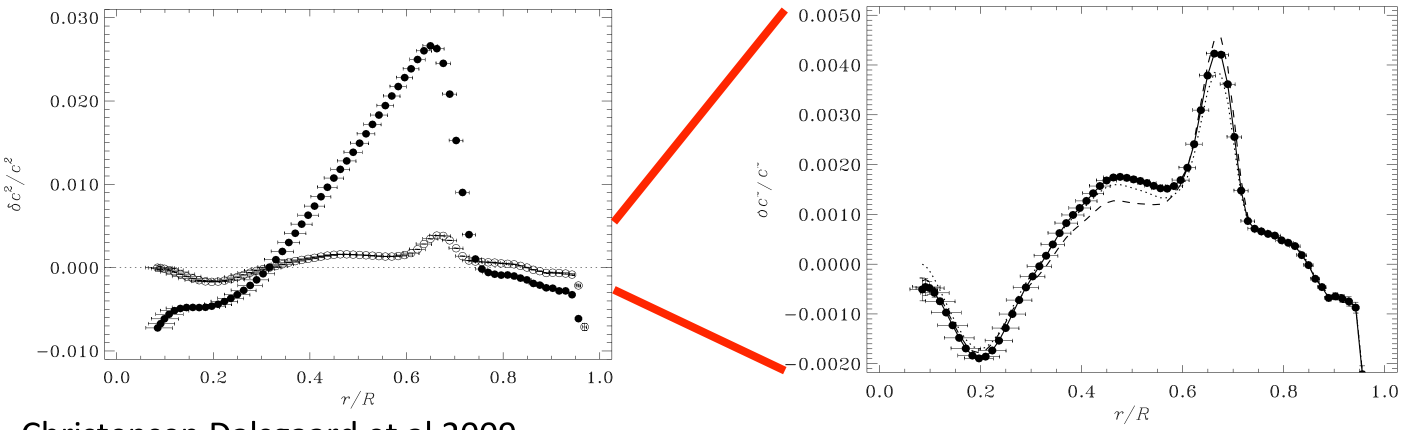


Song et al. in prep.

Solar neutrinos did not differentiate AGSS09 & GS98 models until SF II (2011)
After recent updates in nuclear rates, GS98 preferred
-- > solar neutrinos and seismology now see the same solar structure

But… no information on composition – degeneracy w/opacity

AGSS09 + opacity increase (15 to 20%)



Christensen Dalsgaard et al 2009

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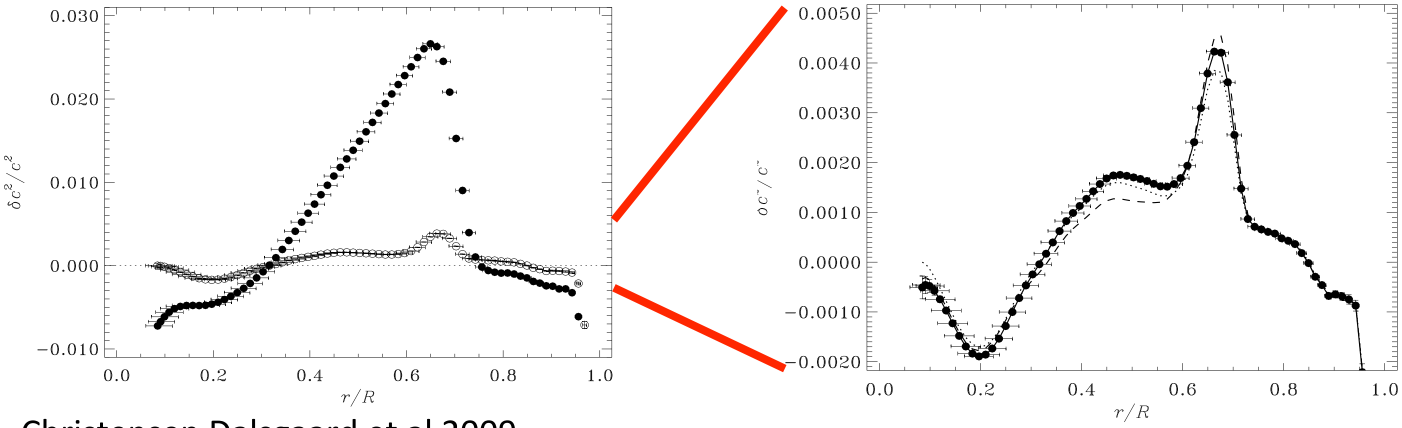

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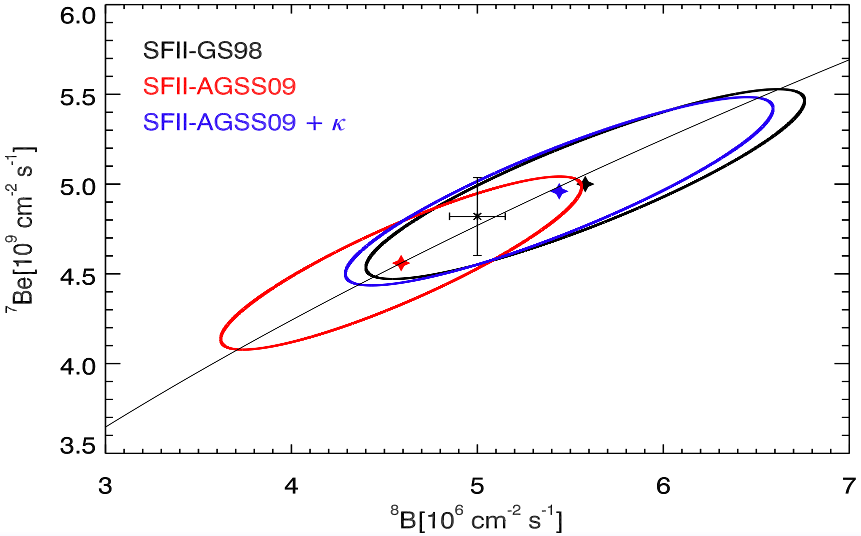
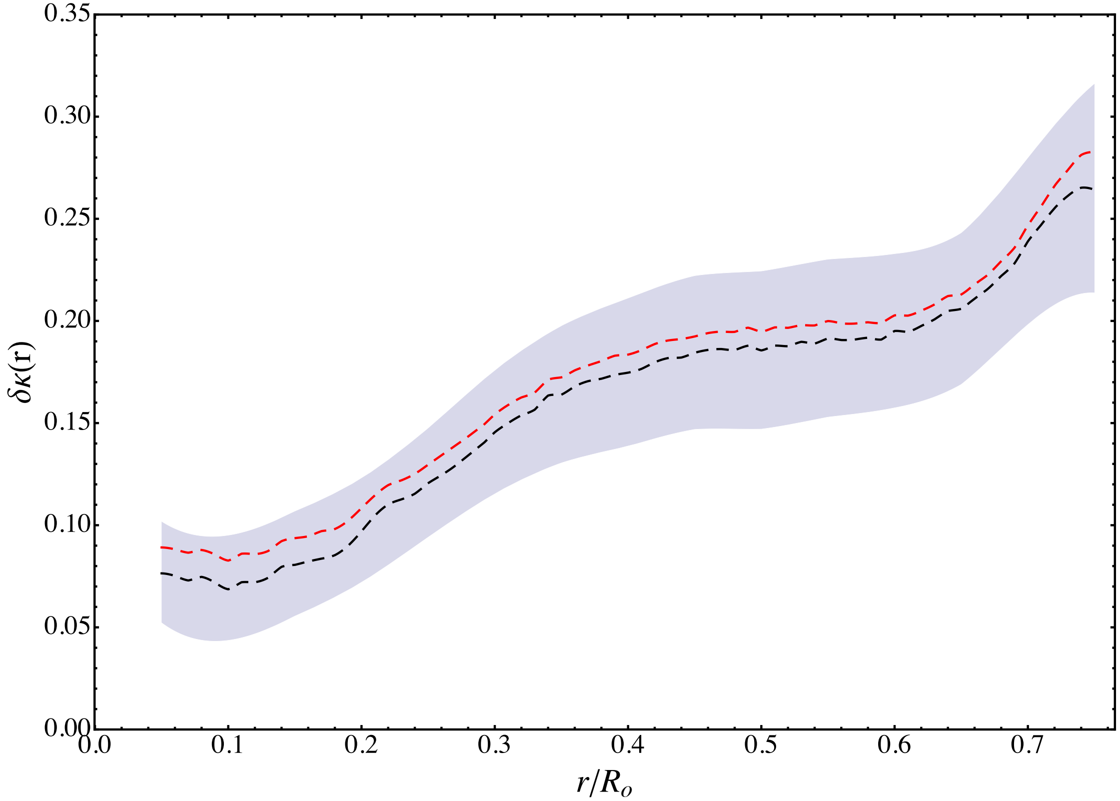


Sound speed and pp-chain neutrinos
-- > recover GS98 “like” values

All probes sensitive to temperature profile not composition

What opacity change?

Using helioseismic data and solar neutrinos – obtain solar opacity profile



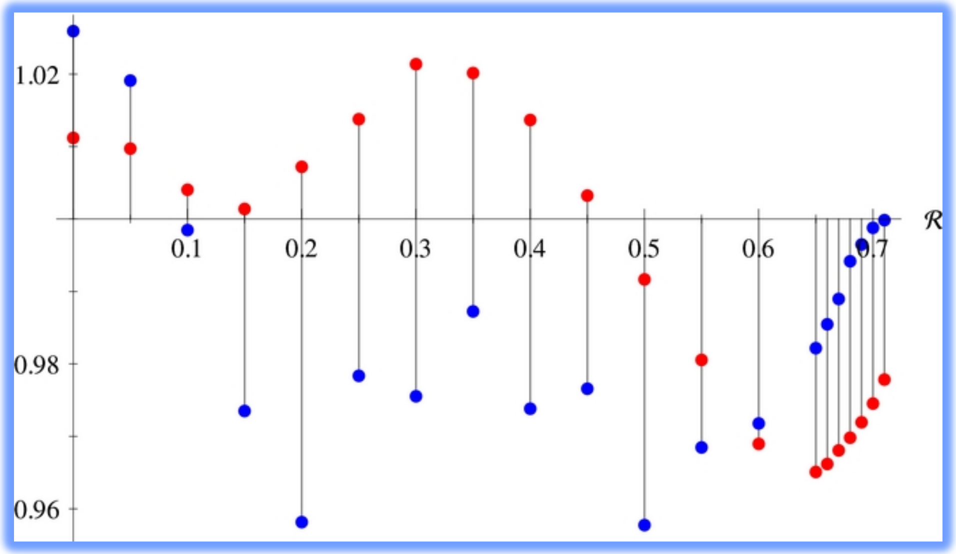
Villante et al. 2014

Fractional opacity difference wrt AGSS09 solar model

few % in the center up to 15-20% at convective boundary

Opacities: theoretical calculations

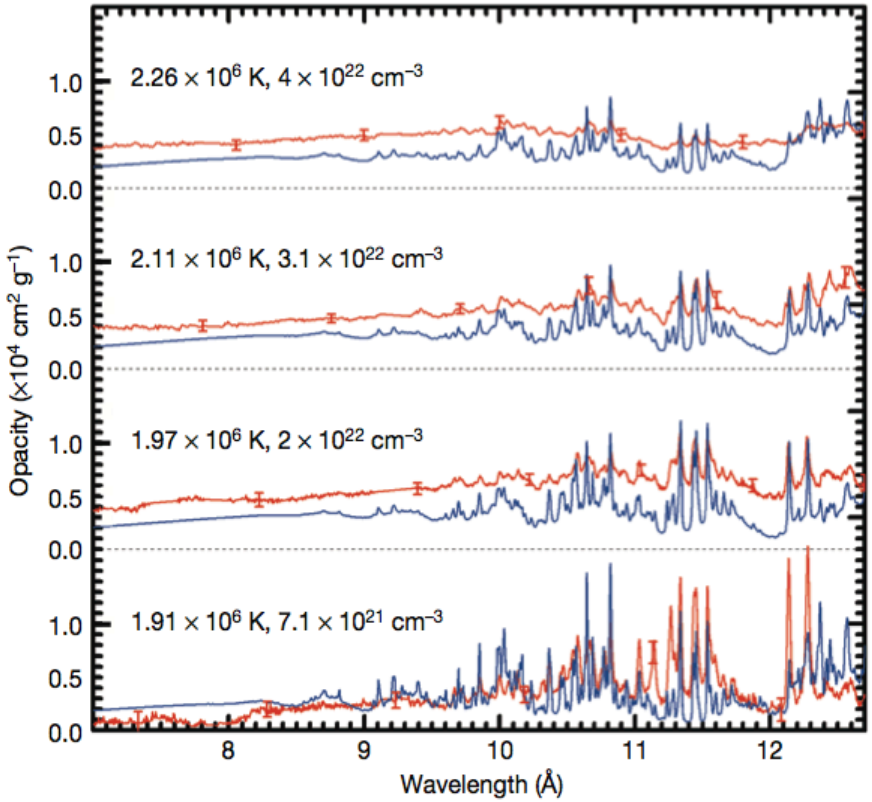
OPAS vs OP (blue) / OPAL vs OP (red)



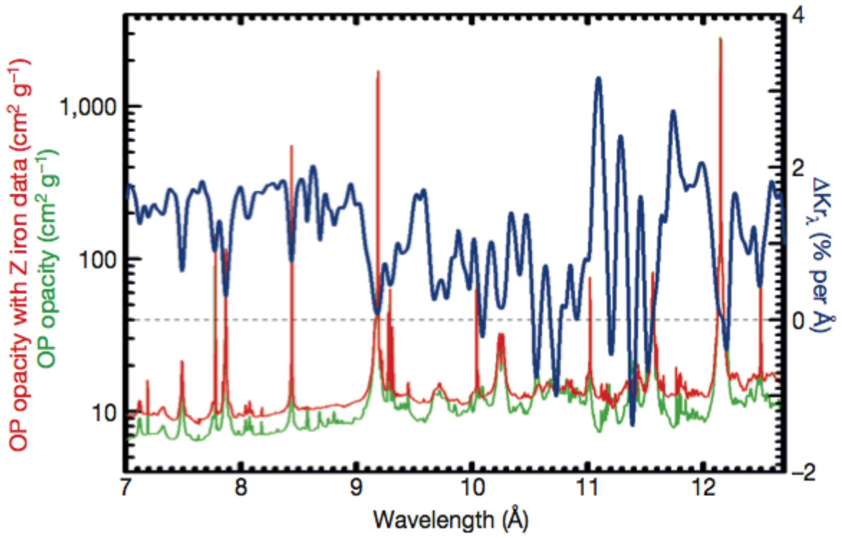
Rosseland mean in solar interior – smallish differences < 4%

Opacities: theoretical calculations

@Sandia lab – Z-facility – conditions close to solar (factor 4 too low in density)
Iron opacity measurements

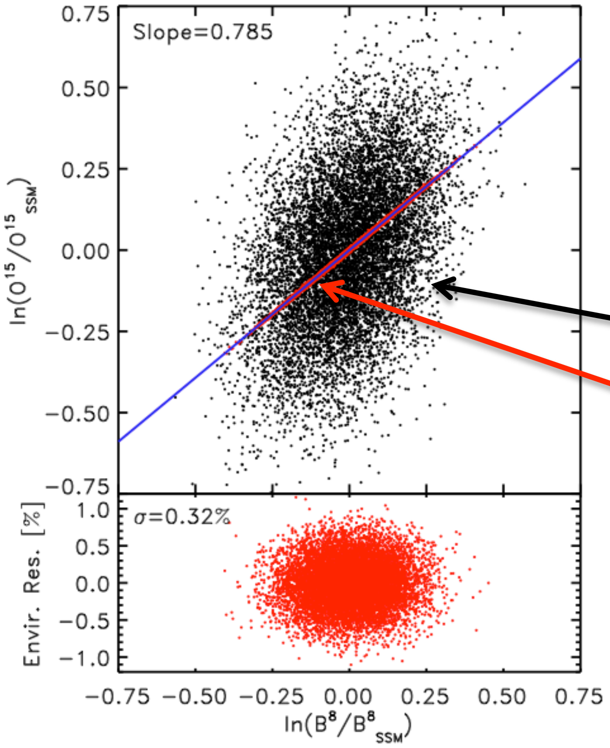


Bailey et al. 2015



When included in Rosseland mean
-- > 7% increase (15-20% needed)

Breaking the degeneracy: CN neutrinos



$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.785} = x_C^{0.794} x_N^{0.212} D^{0.172}$$

$$\times \left[L_\odot^{0.515} O^{-0.016} A^{0.308}\right]$$

→ Temp. dep.

$$\times \left[\mathrm{S}_{11}^{-0.831}\ \mathrm{S}_{33}^{0.342}\ \mathrm{S}_{34}^{-0.685}\ \mathrm{S}_{17}^{-0.785}\ \mathrm{S}_{e7}^{0.785}\ \mathrm{S}_{114}^{0.995}\right]$$

→ Nuclear rates

$$\times \left[x_{\mathrm{O}}^{0.003} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.003} x_{\mathrm{Si}}^{-0.001} x_{\mathrm{S}}^{-0.001} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.003}\right]$$

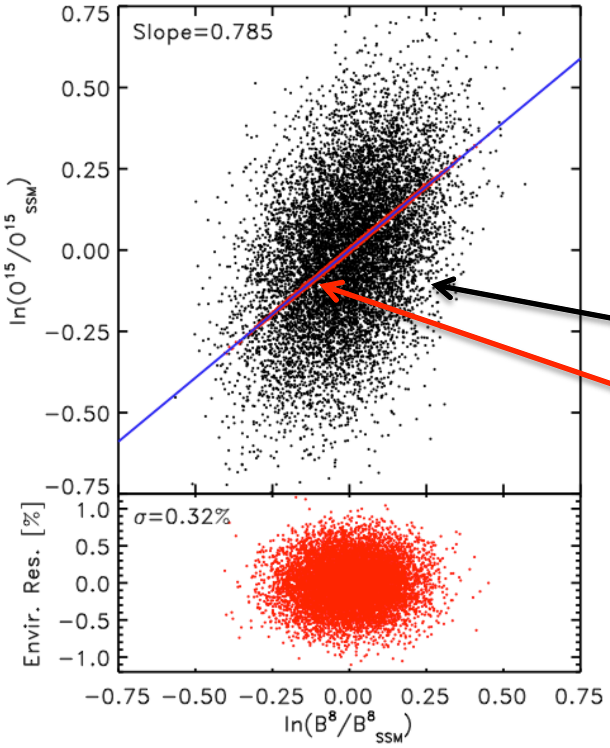
→ Temp. dep.

Complete correlation between ^{15}O – ^{8}B

Only environmental parameters (determine T)

0.3% residuals -- >
if 8B is fixed -- > environmental (T) uncertainty is negligible

Breaking the degeneracy: CN neutrinos



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Nuclear uncertainty: S_{11} & S_{17} (~7% each) + experimental uncertainty in CN fluxes

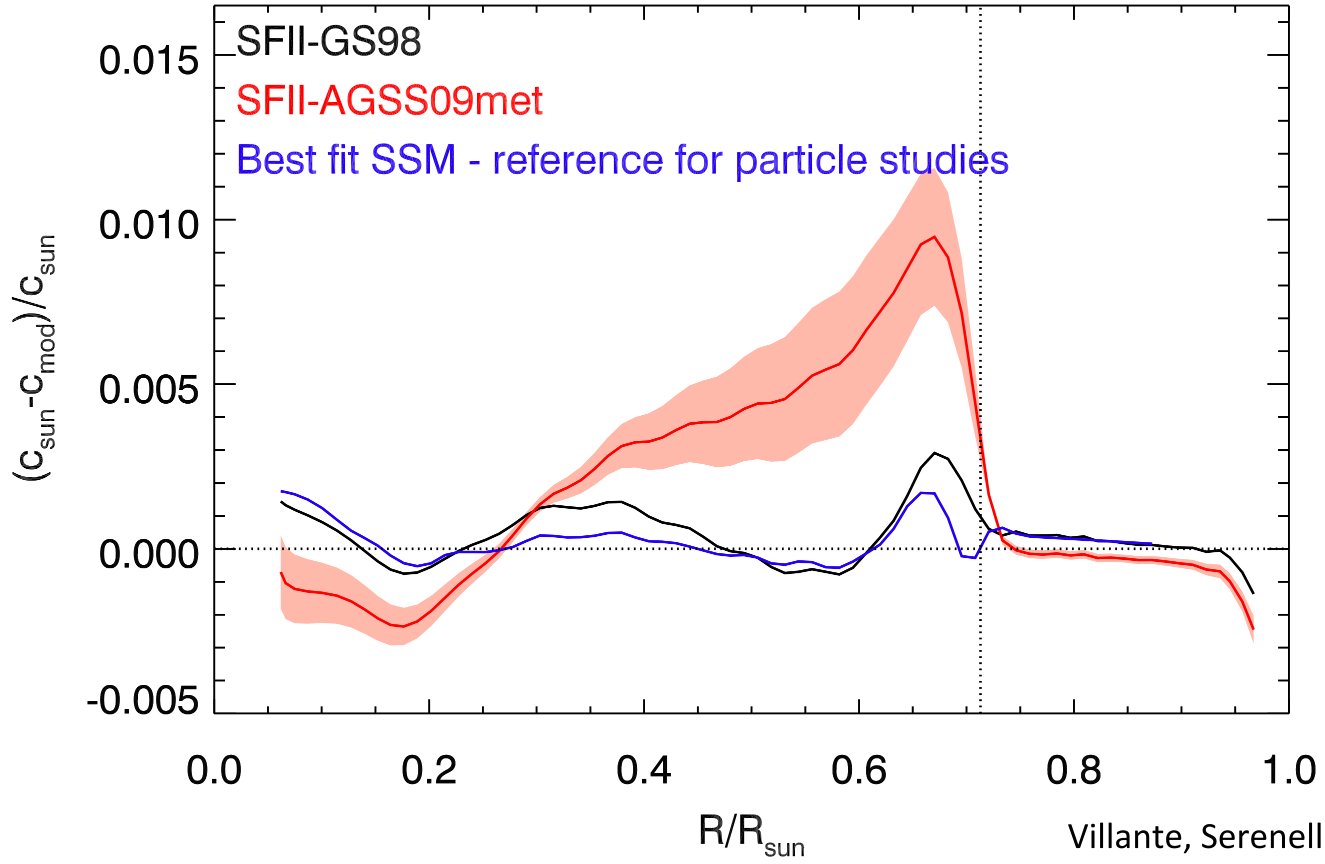
Comparable precision to spectroscopic measurements

Beyond solar composition problem: test for mixing processes in the Sun

Can the SSM be used to make robust inferences (e.g. particle physics)

Allow input parameters vary within uncertainties (e.g. cross sections, gravitational settling)
Let composition (mainly volatiles) or opacities free

Resulting pulls from systematics of order 1 (1-σ) -- > χ^2 = 17 for 34 dof



Villante, Serenelli et al. 2014

Summary

- High (1D) vs Low (3D) solar metallicties:

  Robust helioseismic probes -- > high-Z standard solar models
  SSM with 2011 nuclear rates: pp-chain ν (^{8}B & ^{7}Be) favor both models equally

  Updated nuclear rates -- > High-Z models now favored by solar ν data
  Consistent with helioseismology

However… no direct information on composition – complete degeneracy with opacity

- Opacities
  Theoretical opacity calculations agree within 4%
  Experimental evidence of missing opacity > 7% (iron)

- Neutrinos
  pp-chain fluxes – 8B(3%), 7Be(4.5%), pp(10%), pep(20%)

  CN ν-fluxes a direct probe of central C+N composition @10% level using ^{8}B thermometer
  experimental determination needed

- SSM can be optimized to provide a robust solar profile for studies, e.g., of particle physics

Helioseismology: helium in convective envelope (surface)

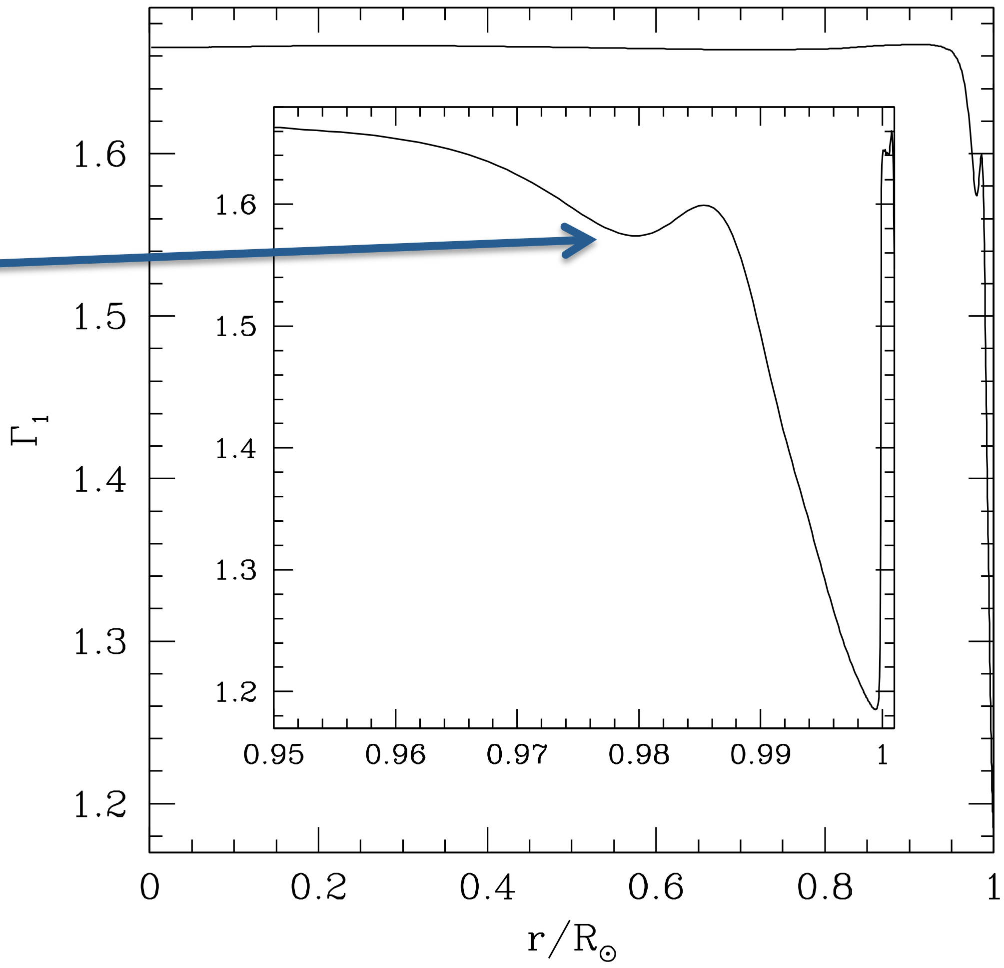
Partial ionization zones leave imprints on Γ_1

HeII dip used to determine surface Y

(modulo EOS & other contributions e.g. OIII)

Y_S in the range 0.24-0.25

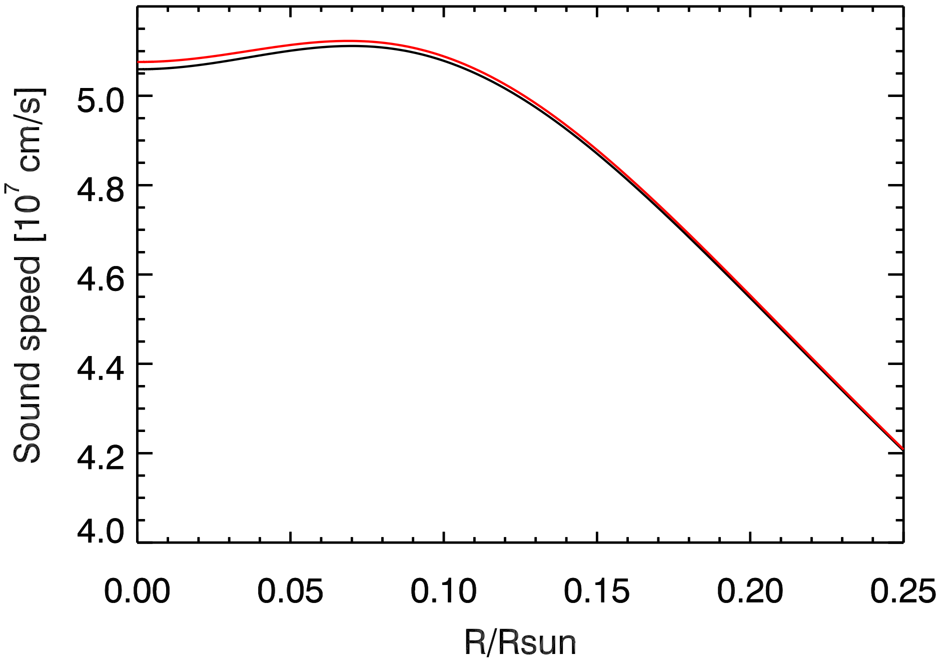
Adopt Y_S=0.2485±0.0034

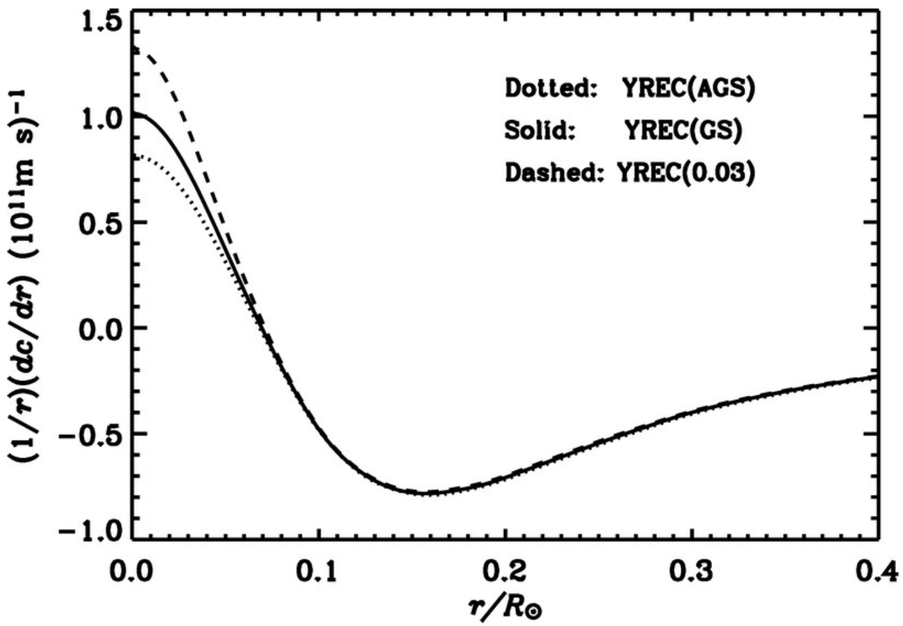


Helioseismology: low degree modes

Low degree modes; l=0, 1, 2, 3 – frequency separation ratios

$$\left.\begin{array}{l} r_{02} = \dfrac{\nu_{n,0}-\nu_{n-1,2}}{\nu_{n,1}-\nu_{n-1,1}} \\[2em] r_{13} = \dfrac{\nu_{n,1}-\nu_{n-1,3}}{\nu_{n+1,0}-\nu_{n,0}} \end{array}\right\} \propto \int_0^R \frac{dc}{dr}\frac{dr}{r}$$





Frequency ratios: probing solar core

Frequency ratios